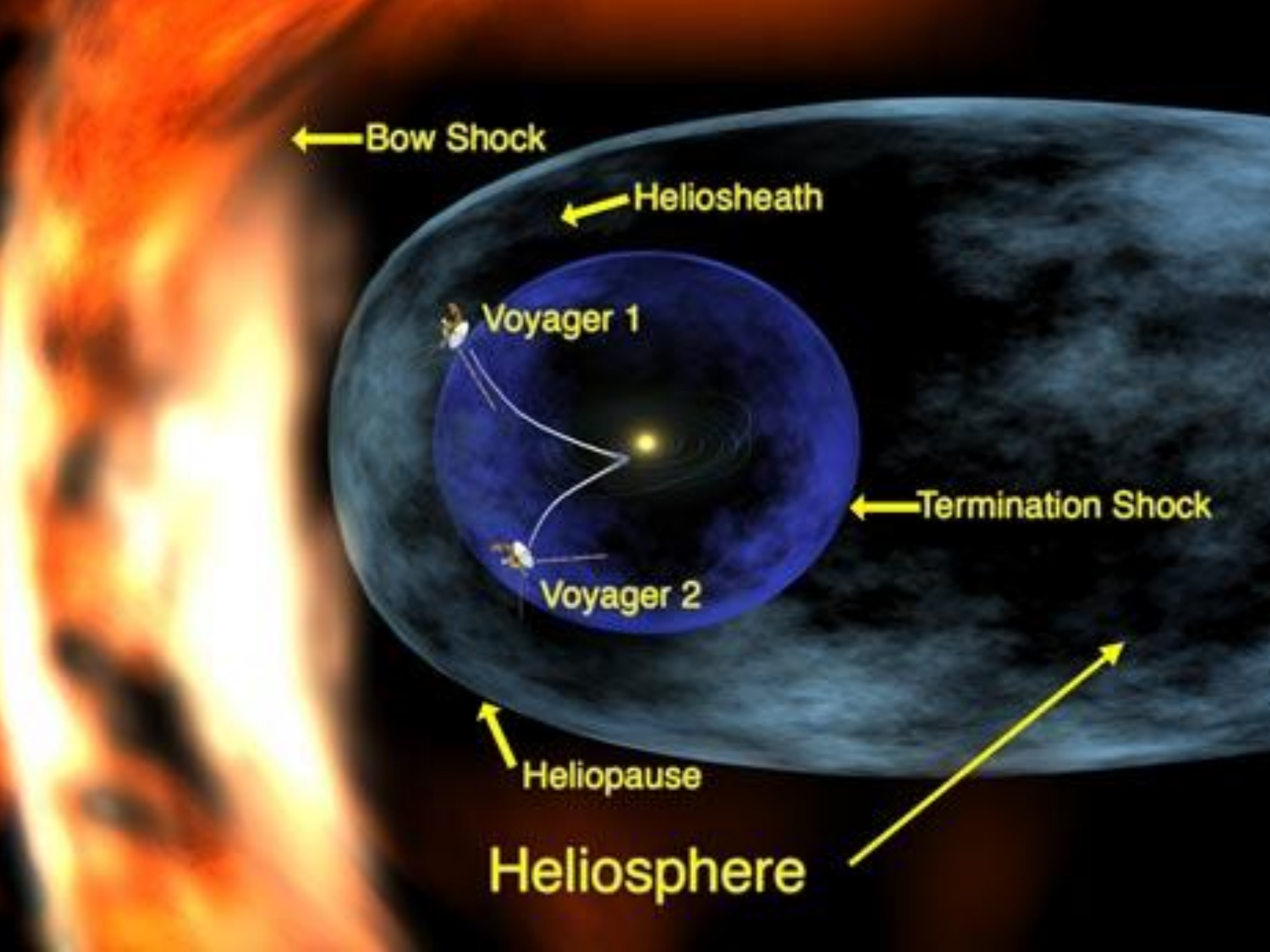
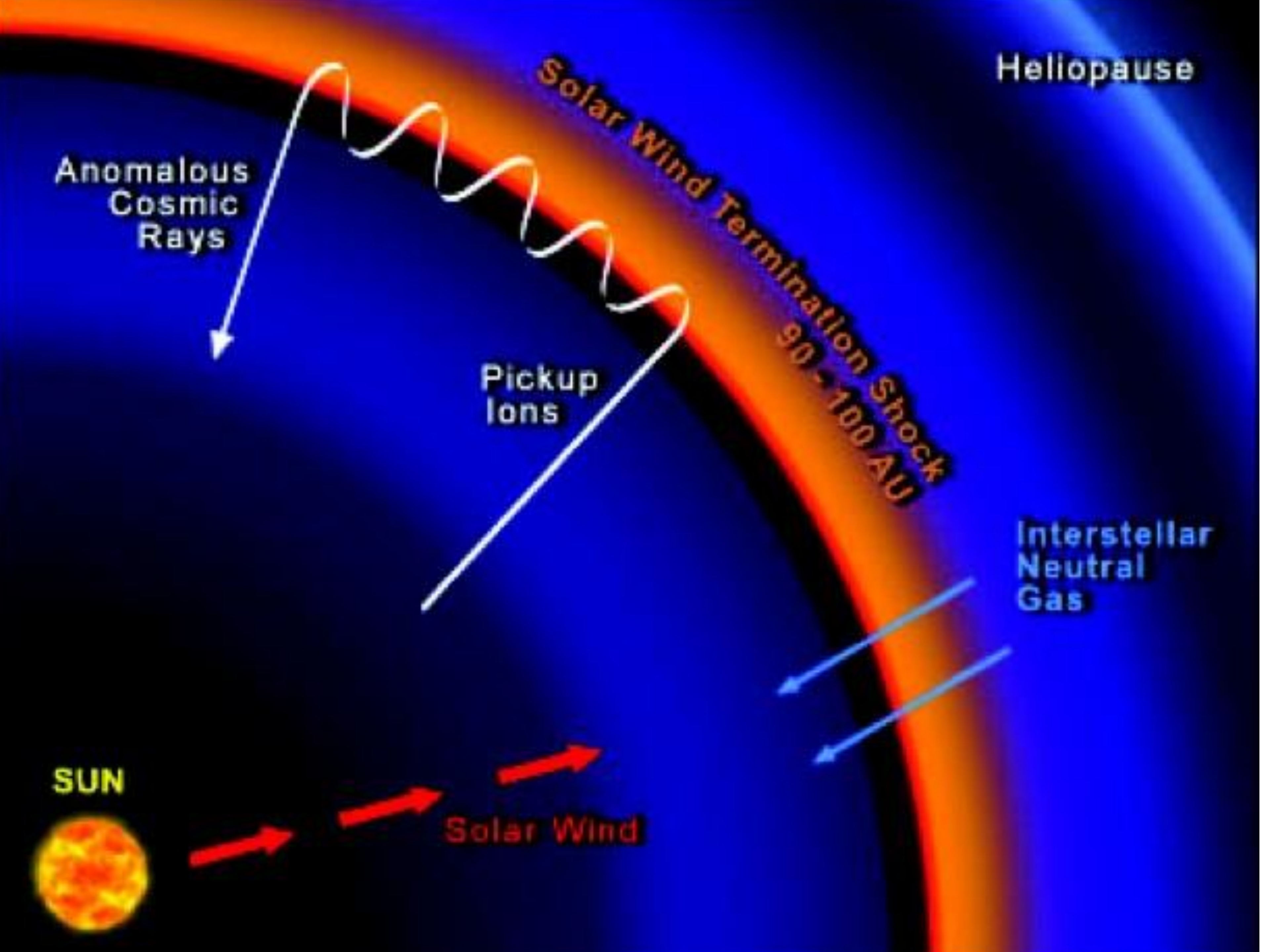
Last time…

- Comments on homework
  - Double epsilons
  - integrals
- Space weather stories
- CMEs

Lecture 36

- Solar wind turbulence
  - Energy spectrum
  - Dimensional analysis
- Heliosphere & termination shock
- Voyager 1 + 2
  - Messages to us & from us
  - Magnetic fields of planets

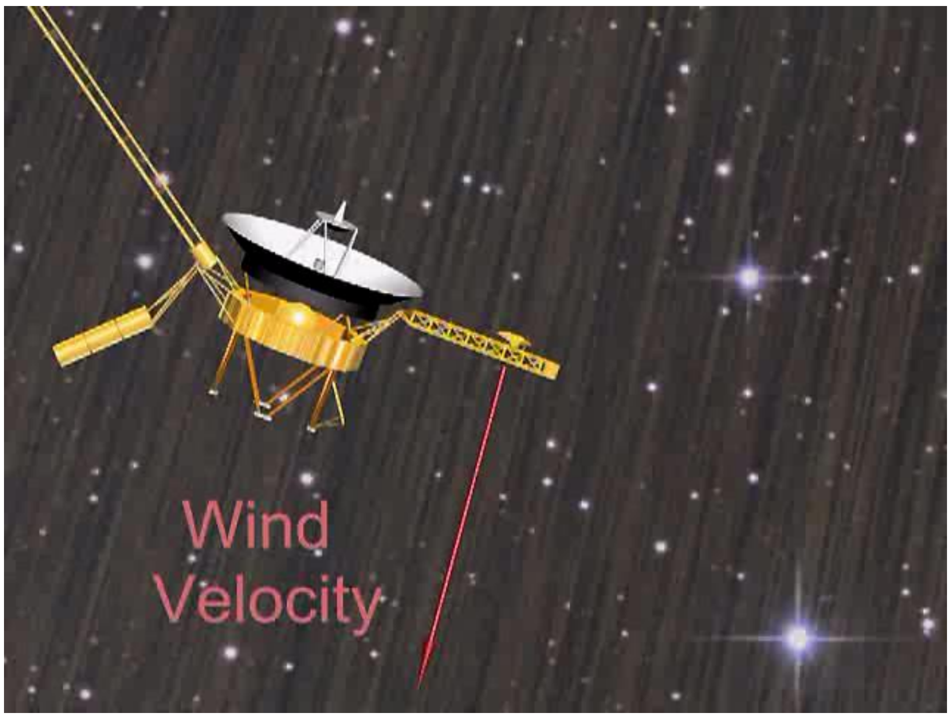

Bow Shock
Heliosheath
Voyager 1
Termination Shock
Voyager 2
Heliopause
Heliosphere

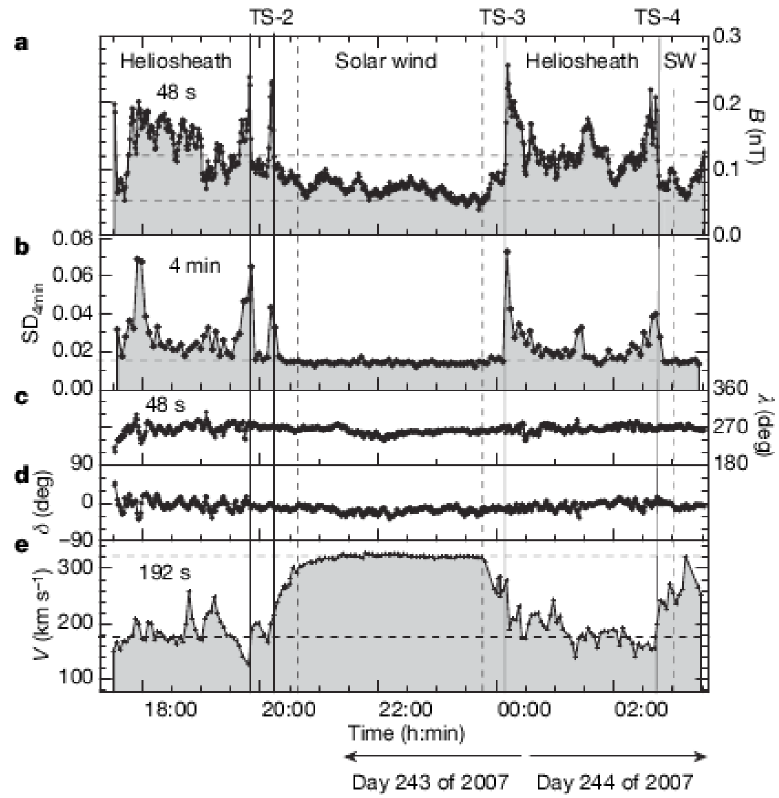


Heliopause
Solar Wind Termination Shock
90 - 100 AU
Anomalous
Cosmic
Rays
Pickup
Ions
Interstellar
Neutral
Gas
SUN
Solar Wind

Magnetic fields at the solar wind termination shock

L. F. Burlaga[1], N. F. Ness[2], M. H. Acuña[1], R. P. Lepping[1], J. E. P. Connerney[1] & J. D. Richardson[3]

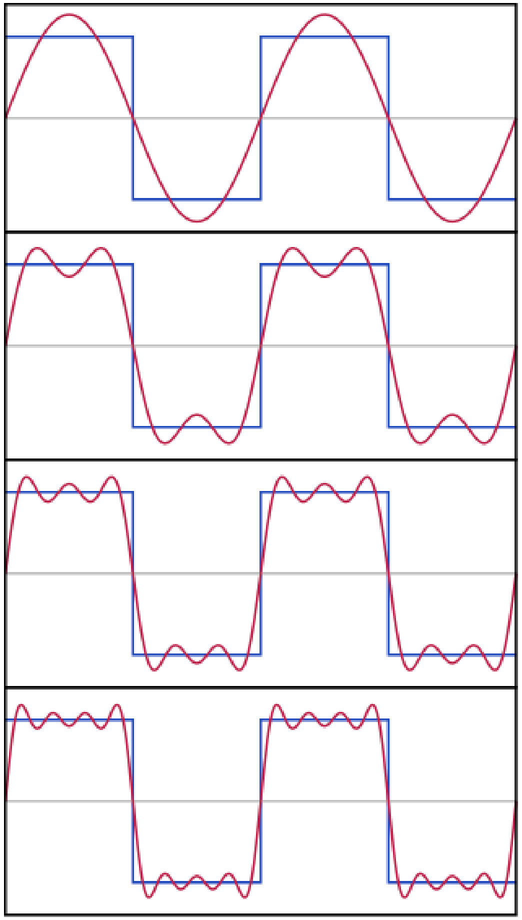




Lect.12: could you explain Fourier analysis?

A. Yes
B. Maybe
C. Probably not
D. Certainly not

$$f(t) = \sum_{n=1}^{\infty} a_n \sin \underbrace{(2\pi n / P)}_{\omega_n} t$$



Lect. 13

$$\Delta\omega = \frac{2\pi}{t_{\max}} \qquad \omega_{\max} \overset{?}{=} \frac{2\pi}{\Delta t} \qquad \omega_{\text{Nyquist}} = \frac{\pi}{\Delta t}$$

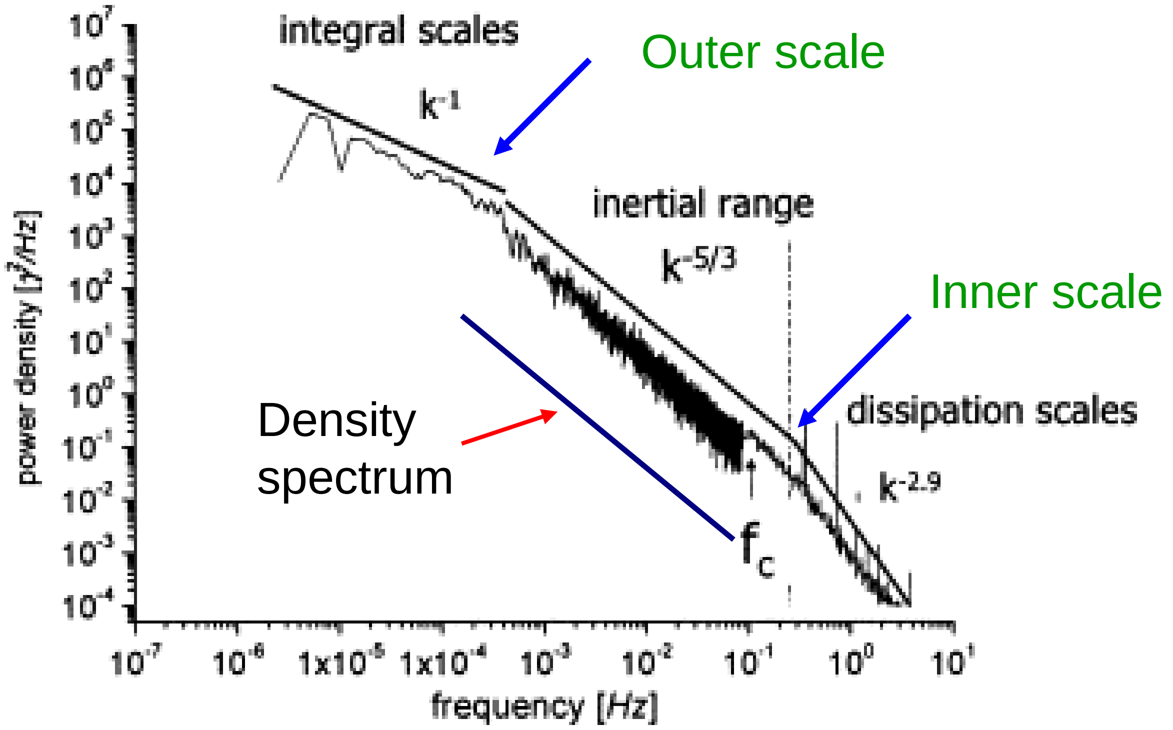
Because there are also negative frequencies

$$-\omega_{\text{Nyquist}} \leq \omega \leq \omega_{\text{Nyquist}} - \Delta\omega$$

- Small wavenumbers → large scales
- Large wavenumbers → small scales

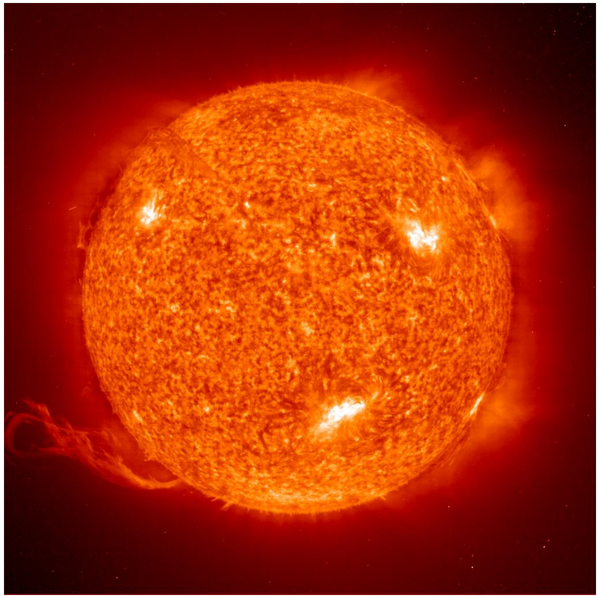
Turbulence spectra measured directly in the solar wind

Magnetic power spectrum

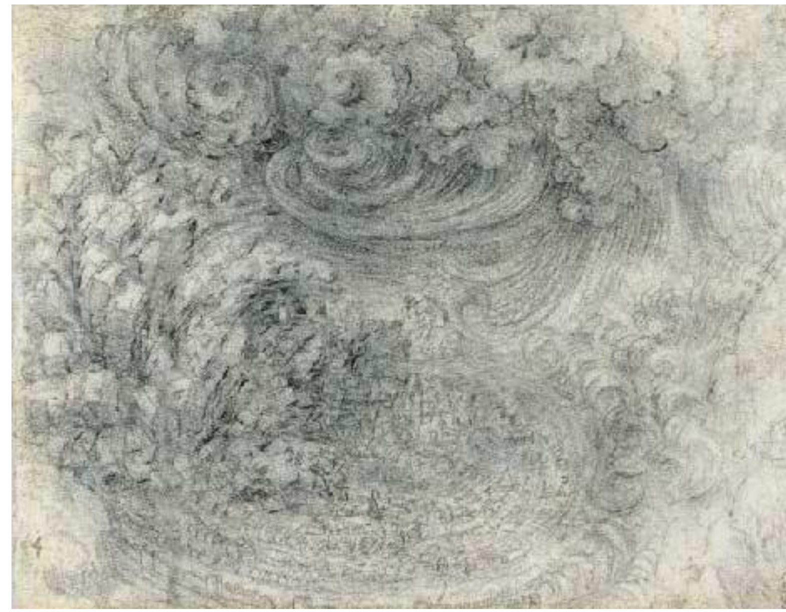


R. Bruno, B. Bavassano, Ad Sp. Res. 35, 939, 2005

turba → confusion, crowd



Da Vinci's conceptions



Large eddies → smaller eddies

Sentimental comments on turbulence

- Werner Heisenberg was asked what he would ask God, given the opportunity. His reply was: "When I meet God, I am going to ask him two questions: Why relativity? And why turbulence? I really believe he will have an answer for the first."
- Horace Lamb—his choice being quantum mechanics (instead of relativity) and turbulence. Lamb was quoted as saying in a speech to the British Association for the Advancement of Science, "I am an old man now, and when I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic."[3]

Hydrodynamic Equations

$$m\frac{d\mathbf{u}}{dt} = \mathbf{F}$$

Newton's equation

$$\rho\frac{D\mathbf{u}}{Dt} = -\nabla p + \mathbf{f} + \mu\nabla^2\mathbf{u}$$

Navier-Stokes equation

$$\mathbf{u} = \mathbf{u}(t, \mathbf{x})$$

chain rule

$$\frac{D\mathbf{u}}{Dt} = \frac{\partial\mathbf{u}}{\partial t} + \frac{\partial x_j}{\partial t}\frac{\partial\mathbf{u}}{\partial x_j}$$

$$= \frac{\partial\mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}$$

Reynolds number

$$\frac{|\mathbf{u}\cdot\nabla\mathbf{u}|}{|\nu\nabla^2\mathbf{u}|} \sim \frac{ul}{\nu} \equiv \mathrm{Re}$$

$\nu = \mu/\rho$

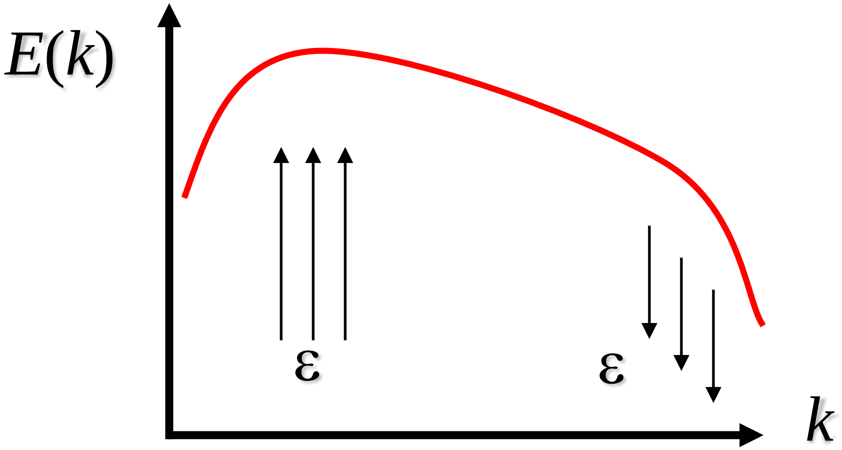
Kolmogorov spectrum

nonlinearity

$$(\cos kx)^2 = \tfrac{1}{2}\cos 2kx + \tfrac{1}{2}$$

$$k \to 2k$$

constant flux ε [cm²/s³]



$$\int E(k)\,dk = \tfrac{1}{2}\langle \mathbf{u}^2 \rangle \qquad [\mathrm{cm}^3/\mathrm{s}^2]$$

$$E(k) = C_K \varepsilon^a k^b$$

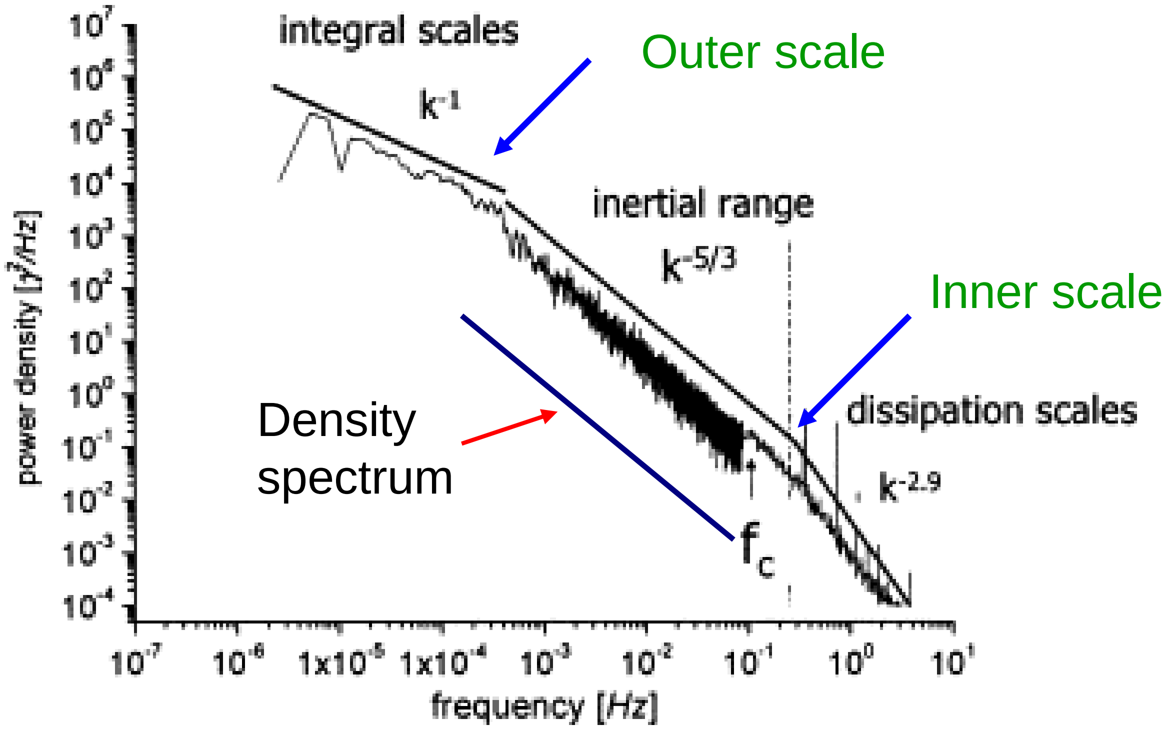
$$\mathrm{cm}: \quad 3 = 2a - 1$$

$$\mathrm{s}: \quad 2 = 3a$$

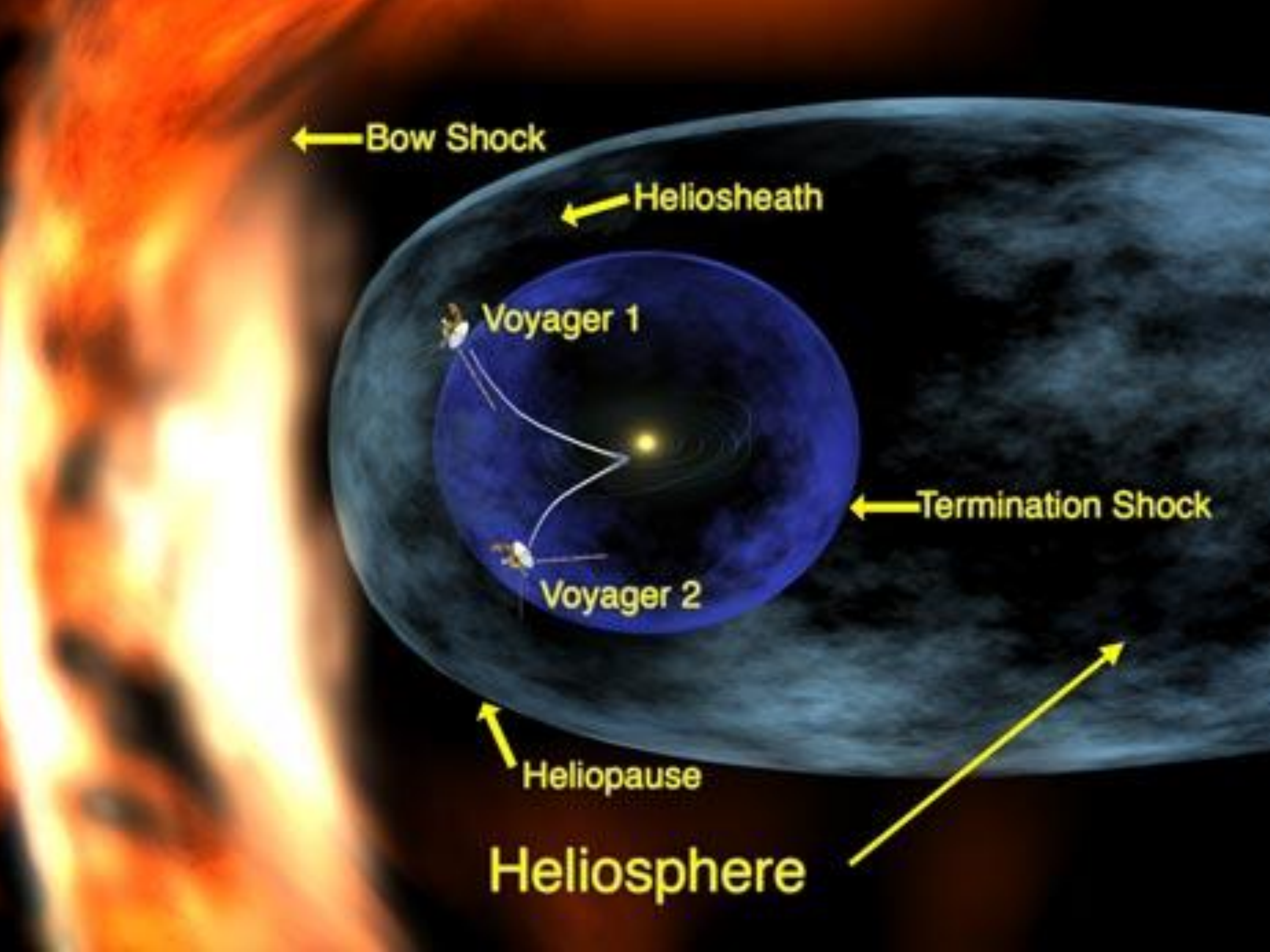
$a=2/3$, $b=-5/3$

Turbulent spectra can be measured directly in the solar wind

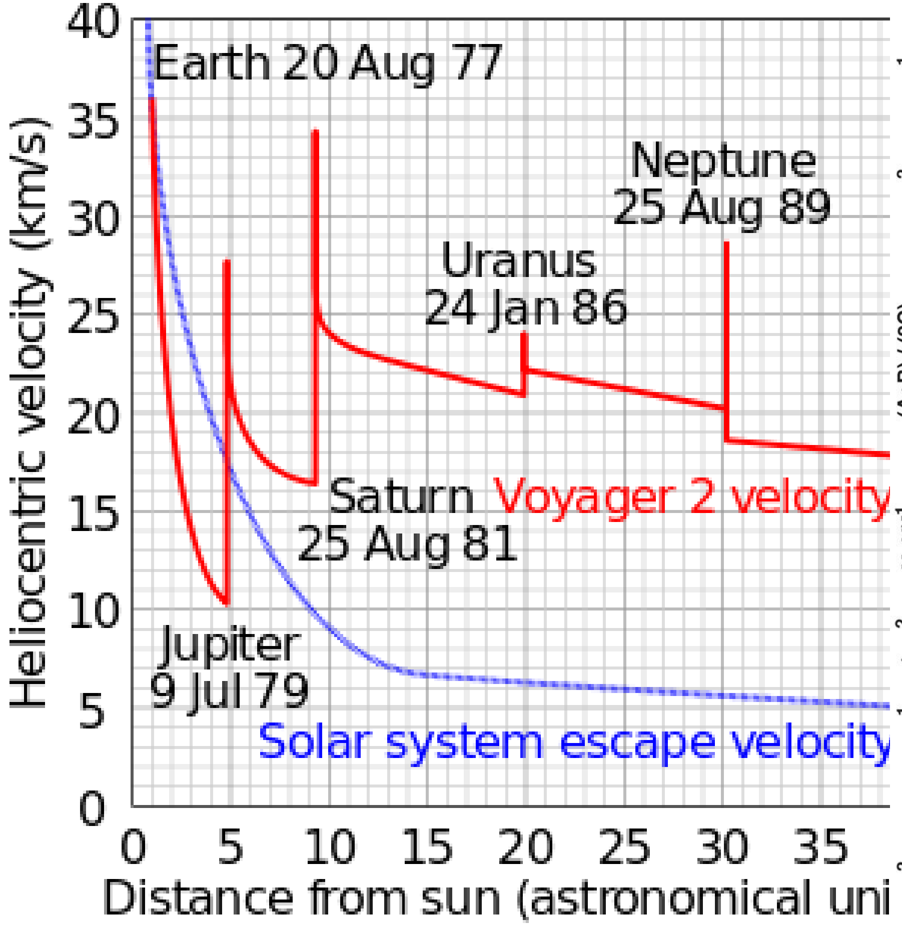
Magnetic power spectrum

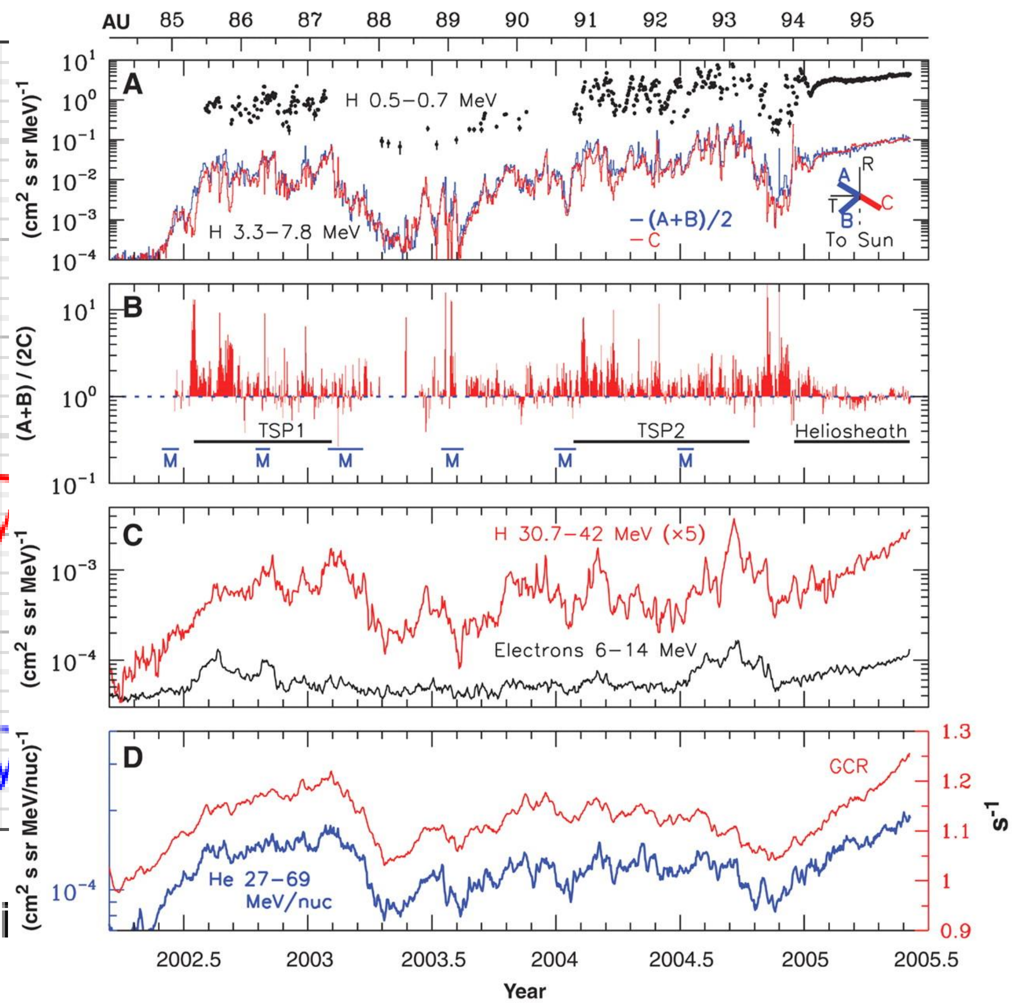


R. Bruno, B. Bavassano, Ad Sp. Res. 35, 939, 2005


Bow Shock
Heliosheath
Voyager 1
Termination Shock
Voyager 2
Heliopause
Heliosphere

Voyager 2


Earth 20 Aug 77
Neptune 25 Aug 89
Uranus 24 Jan 86
Saturn 25 Aug 81
Voyager 2 velocity
Jupiter 9 Jul 79
Solar system escape velocity
Heliocentric velocity (km/s)
Distance from sun (astronomical uni


AU
H 0.5–0.7 MeV
H 3.3–7.8 MeV
– (A+B)/2
– C
To Sun
TSP1
TSP2
Heliosheath
H 30.7–42 MeV (×5)
Electrons 6–14 MeV
GCR
He 27–69 MeV/nuc
Year

The latest from Voyager 2

THE ASTROPHYSICAL JOURNAL, 818:147 (16pp), 2016 February 20
doi:10.3847/0004-637X/818/2/147

CrossMark

HELIOSHEATH MAGNETIC FIELD AND PLASMA OBSERVED BY *VOYAGER* 2 DURING 2012 IN THE RISING PHASE OF SOLAR CYCLE 24

L. F. BURLAGA[1], N. F. NESS[2], J. D. RICHARDSON[3], R. B. DECKER[4], AND S. M. KRIMIGIS[4]
[1] NASA Goddard Space Flight Center, Greenbelt, Maryland, USA
[2] Institute for Astrophysics and Computational Sciences, Catholic University of America, Washington, District of Columbia, USA
[3] Kavli Center for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[4] Johns Hopkins University, Applied Physics Laboratory, Laurel, Maryland, USA
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ABSTRACT

We discuss magnetic field and plasma observations of the heliosheath made by *Voyager 2* (*V2*) during 2012, when *V2* was observing the effects of increasing solar activity following the solar minimum in 2009. The average magnetic field strength B was 0.14 nT and B reached 0.29 nT on day 249. *V2* was in a unipolar region in which the magnetic polarity was directed away from the Sun along the Parker spiral 88% of the time, indicating that *V2* was poleward of the heliospheric current sheet throughout most of 2012. The magnetic flux at *V2* during 2012 was constant. A merged interaction region (MIR) was observed, and the flow speed increased as the MIR moved past *V2*. The MIR caused a decrease in the >70 MeV nuc^{-1} cosmic-ray intensity. The increments of B can be described by a q-Gaussian distribution with $q = 1.2 \pm 0.1$ for daily averages and $q = 1.82 \pm 0.03$ for hour averages. Eight isolated current sheets ("PBLs") and four closely spaced pairs of current sheets were observed. The average change of B across the current sheets was a factor of ≈2, and B increased or decreased with equal probability. Magnetic holes and magnetic humps were also observed. The characteristic size of the PBLs was ≈6 R_L, where R_L is the Larmor radius of protons, and the characteristic sizes of the magnetic holes and humps were ≈38 R_L and ≈11 R_L, respectively.

Key words: magnetic fields – plasmas – Sun: heliosphere

Voyager 2

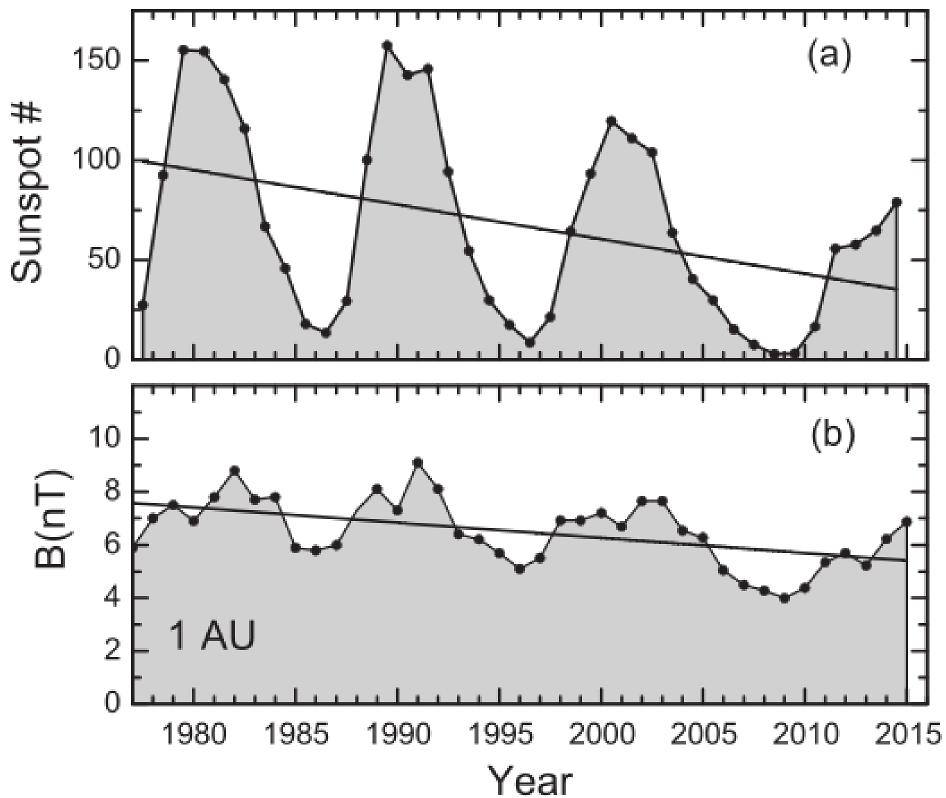


Figure 3. Yearly averages of (a) the sunspot number and (b) magnetic field strength observed at 1 au show the tendency for solar activity to decrease from 1977 to 2015 and the corresponding tendency for *B* at 1 au to decrease. The solar activity and *B* reached a minimum at 1 au during 2009 and they have been increasing since 2010. It takes approximately one year for the magnetic fields and plasma observed at 1 au to reach *V2* during 2012.

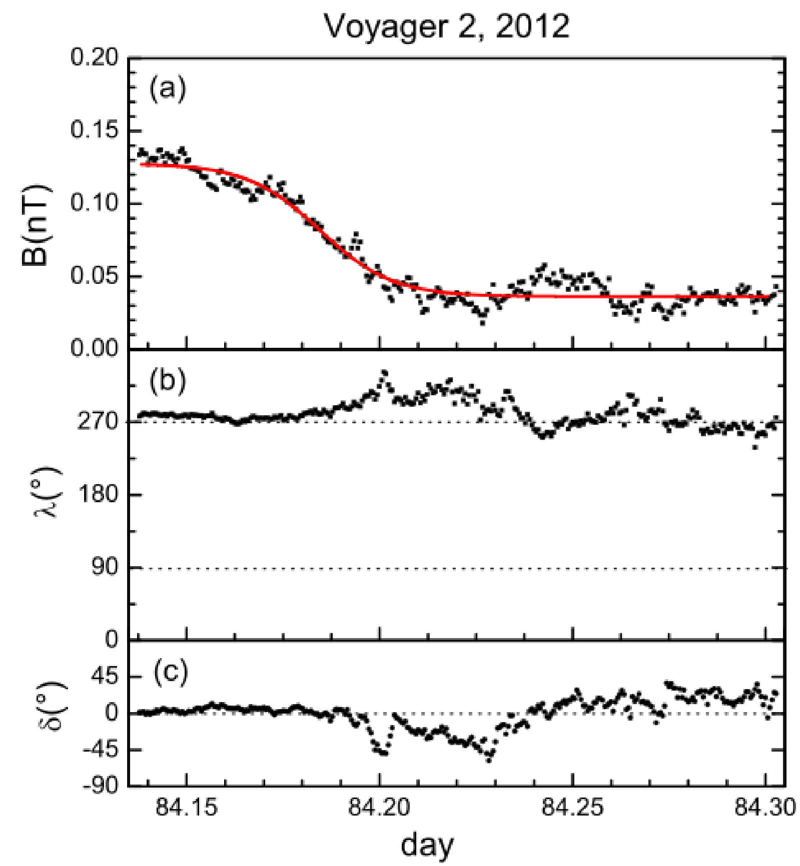


Figure 11. Proton boundary layer across which (a) *B* decreased and there was little or no net change across in (b) the angle λ or (c) the angle δ. The data points are 48 s averages of $\boldsymbol{B}$.

How far is Voyager 1 now?

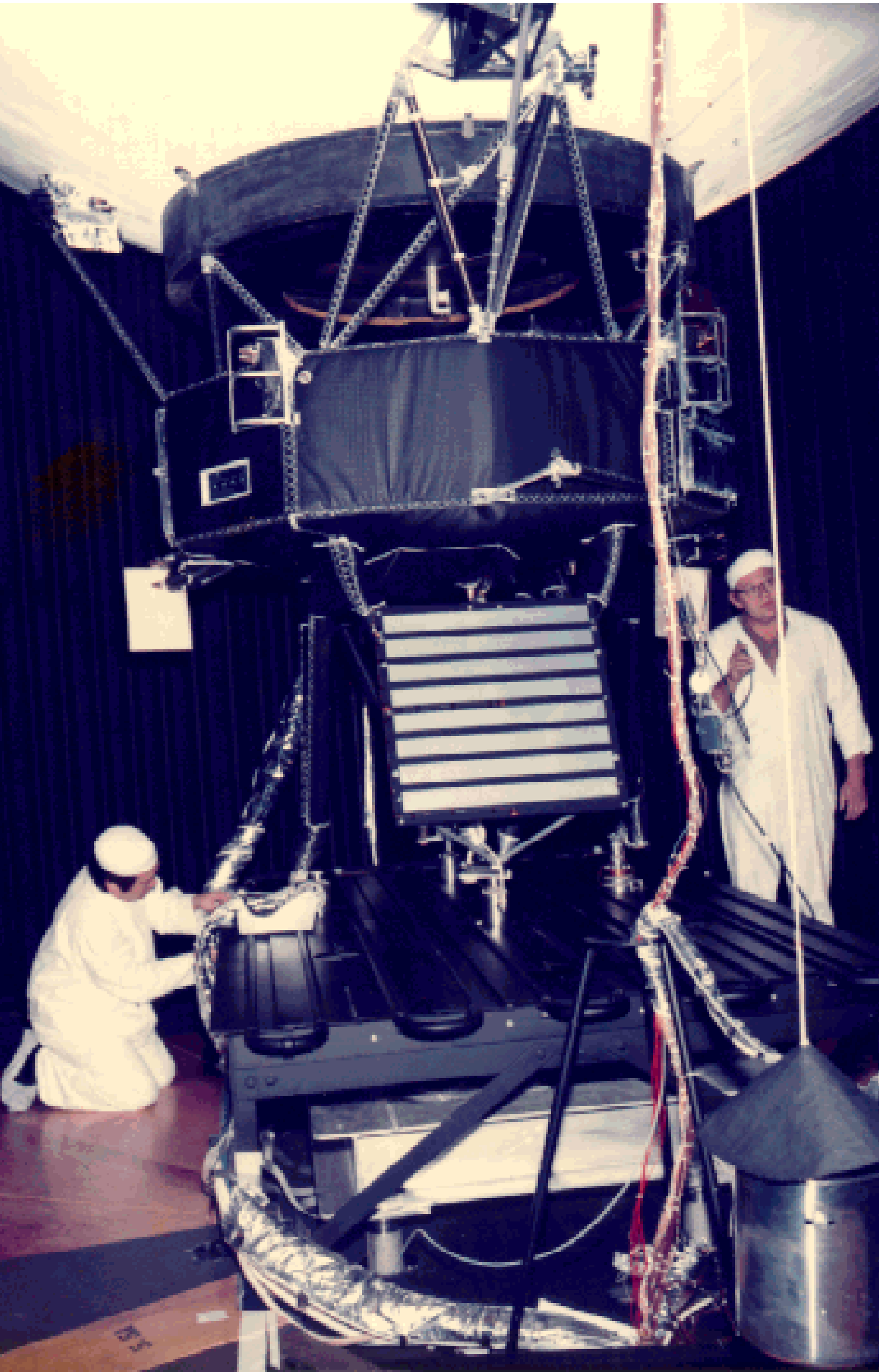
A. 62 AU
B. 76 AU
C. 82 AU
D. 134 AU
E. 153 AU

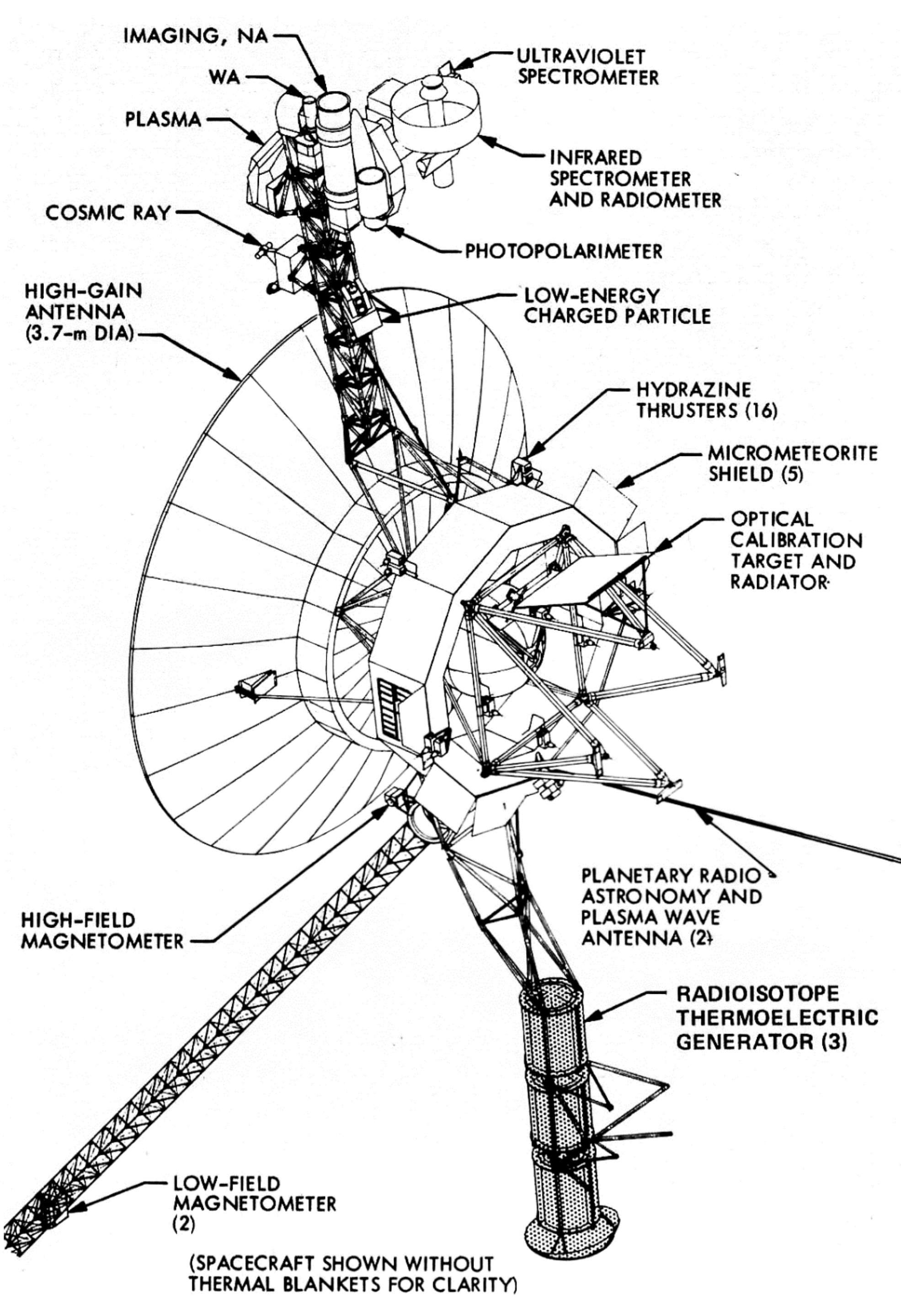
When was it launched

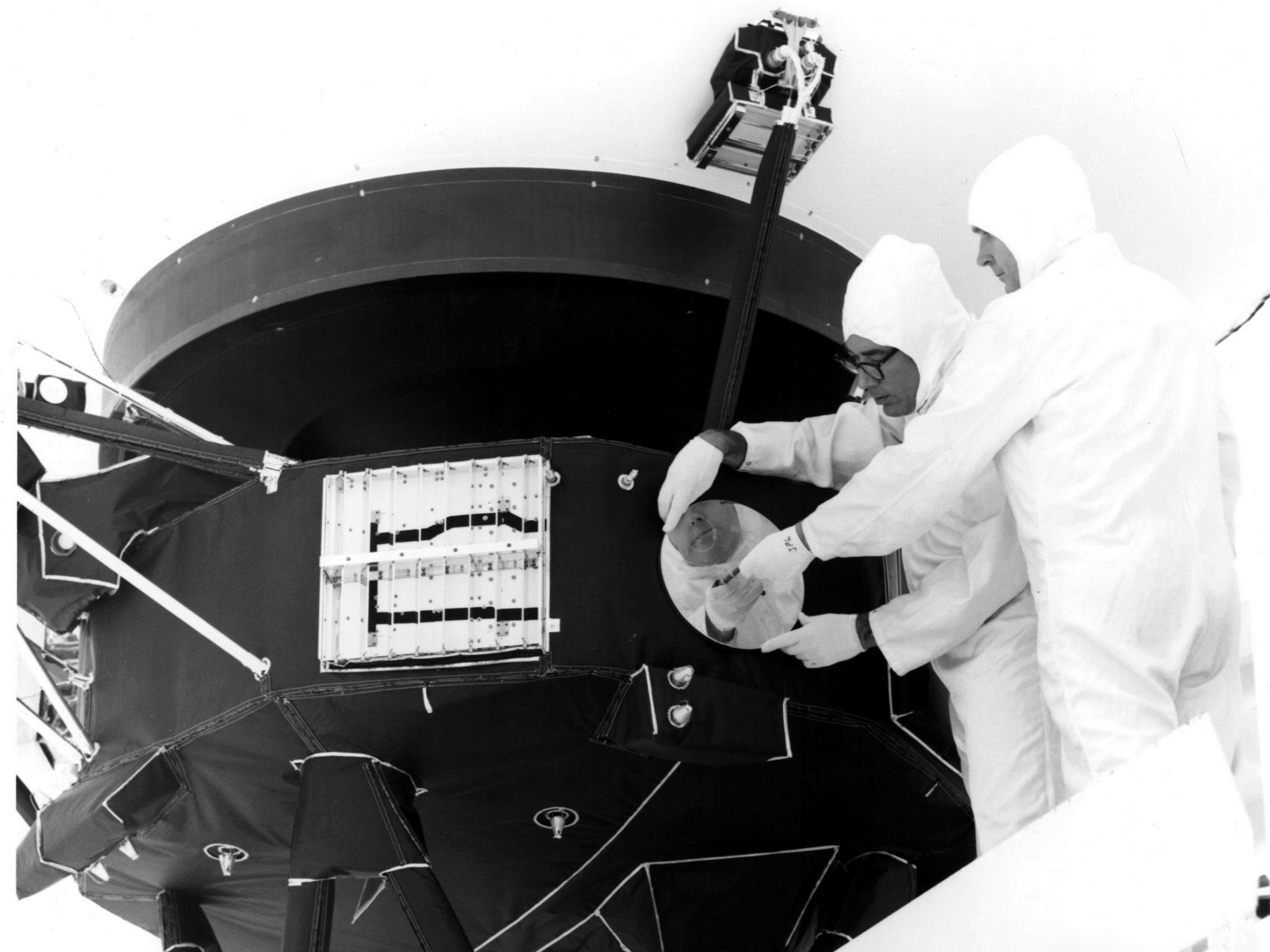
A. 1967
B. 1977
C. 1987
D. 1997
E. 2007

Voyager 1+2

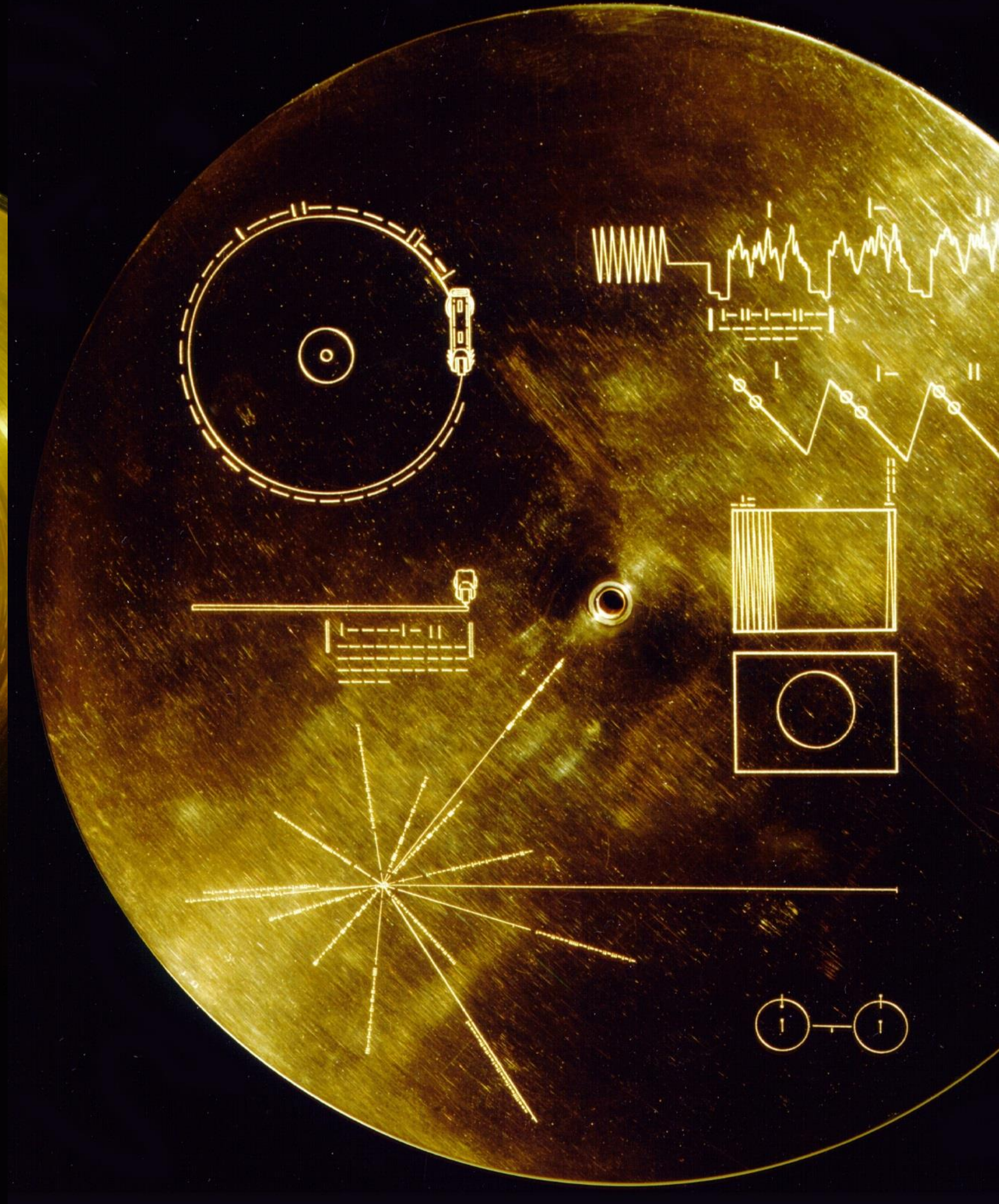
- Voyager 1: Sept 5, 1977
  - Most distant (134 AU, 37 lh/2)
  - North (Saturn in 1980)
  - Nuclear batteries until 2020
- Voyager 2
  - Jupiter, Saturn, Uranus, Neptune!
  - South (Uranus in 1986)
  - 110 AU, 15 km/s



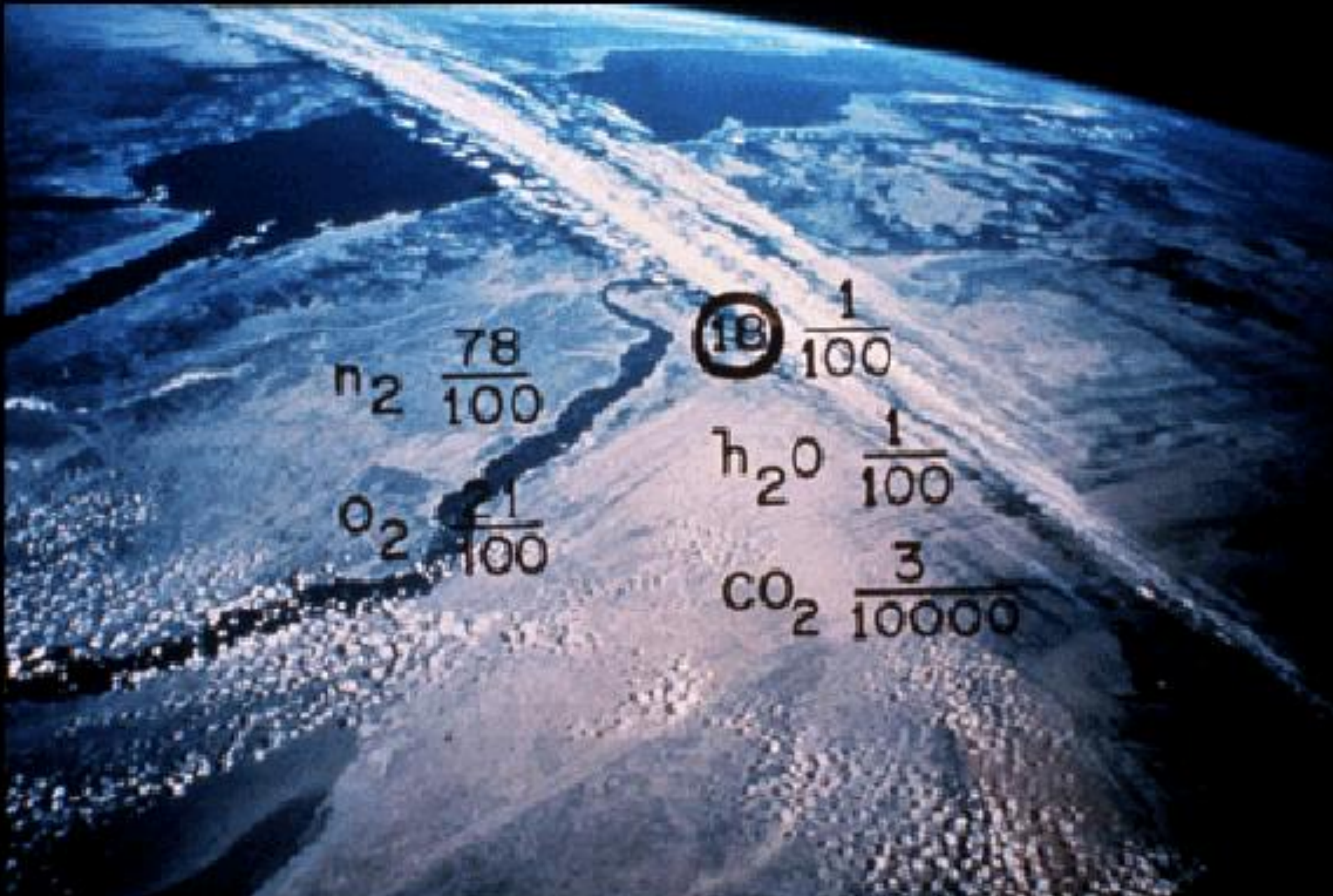

IMAGING, NA
WA
PLASMA
ULTRAVIOLET SPECTROMETER
INFRARED SPECTROMETER AND RADIOMETER
COSMIC RAY
PHOTOPOLARIMETER
HIGH-GAIN ANTENNA (3.7-m DIA)
LOW-ENERGY CHARGED PARTICLE
HYDRAZINE THRUSTERS (16)
MICROMETEORITE SHIELD (5)
OPTICAL CALIBRATION TARGET AND RADIATOR
PLANETARY RADIO ASTRONOMY AND PLASMA WAVE ANTENNA (2)
HIGH-FIELD MAGNETOMETER
RADIOISOTOPE THERMOELECTRIC GENERATOR (3)
LOW-FIELD MAGNETOMETER (2)
(SPACECRAFT SHOWN WITHOUT THERMAL BLANKETS FOR CLARITY)


JPL


THE SOUNDS OF EARTH
Side 1
UNITED STATES OF AMERICA
PLANET EARTH



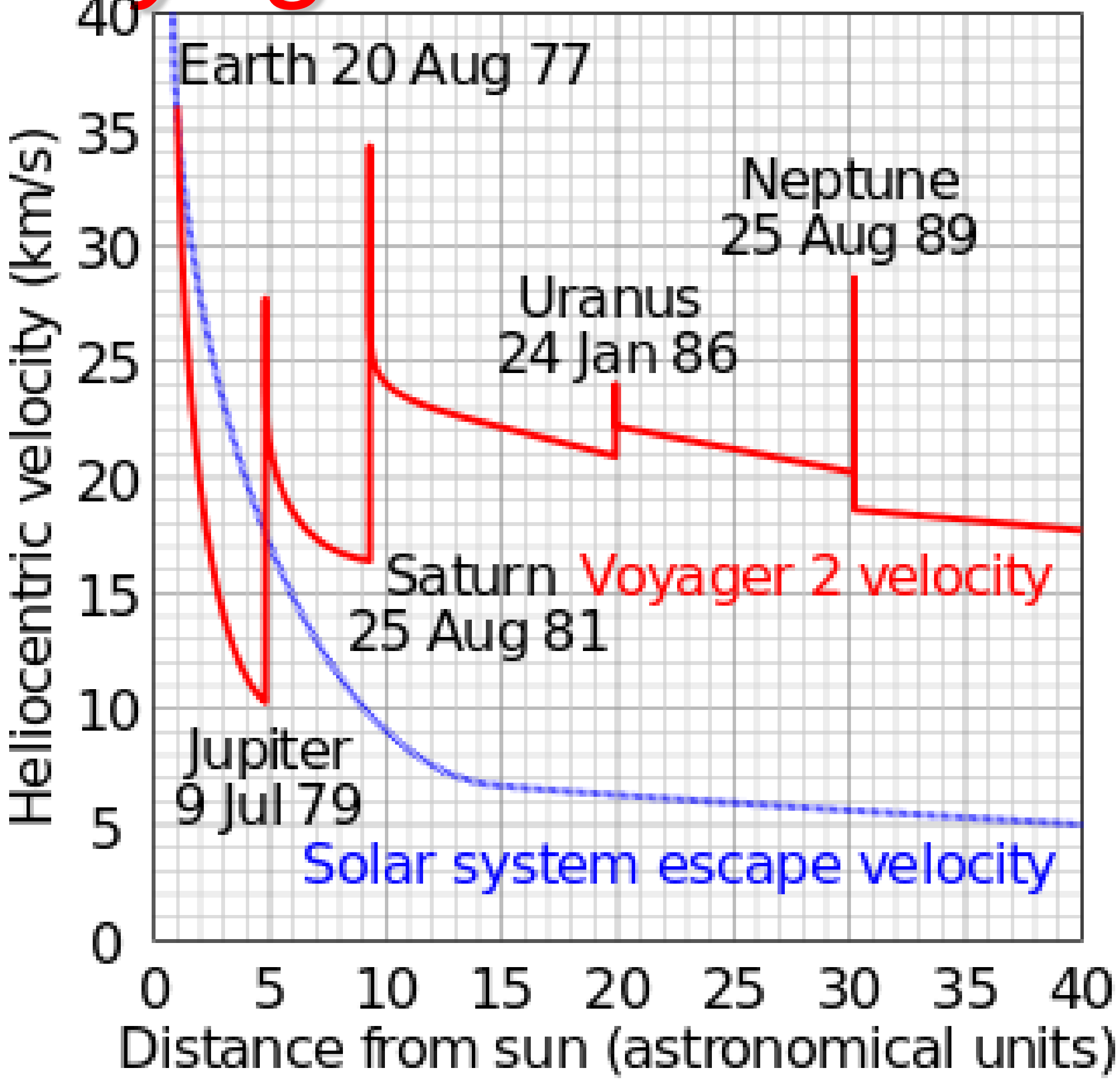

142800 km
318 e



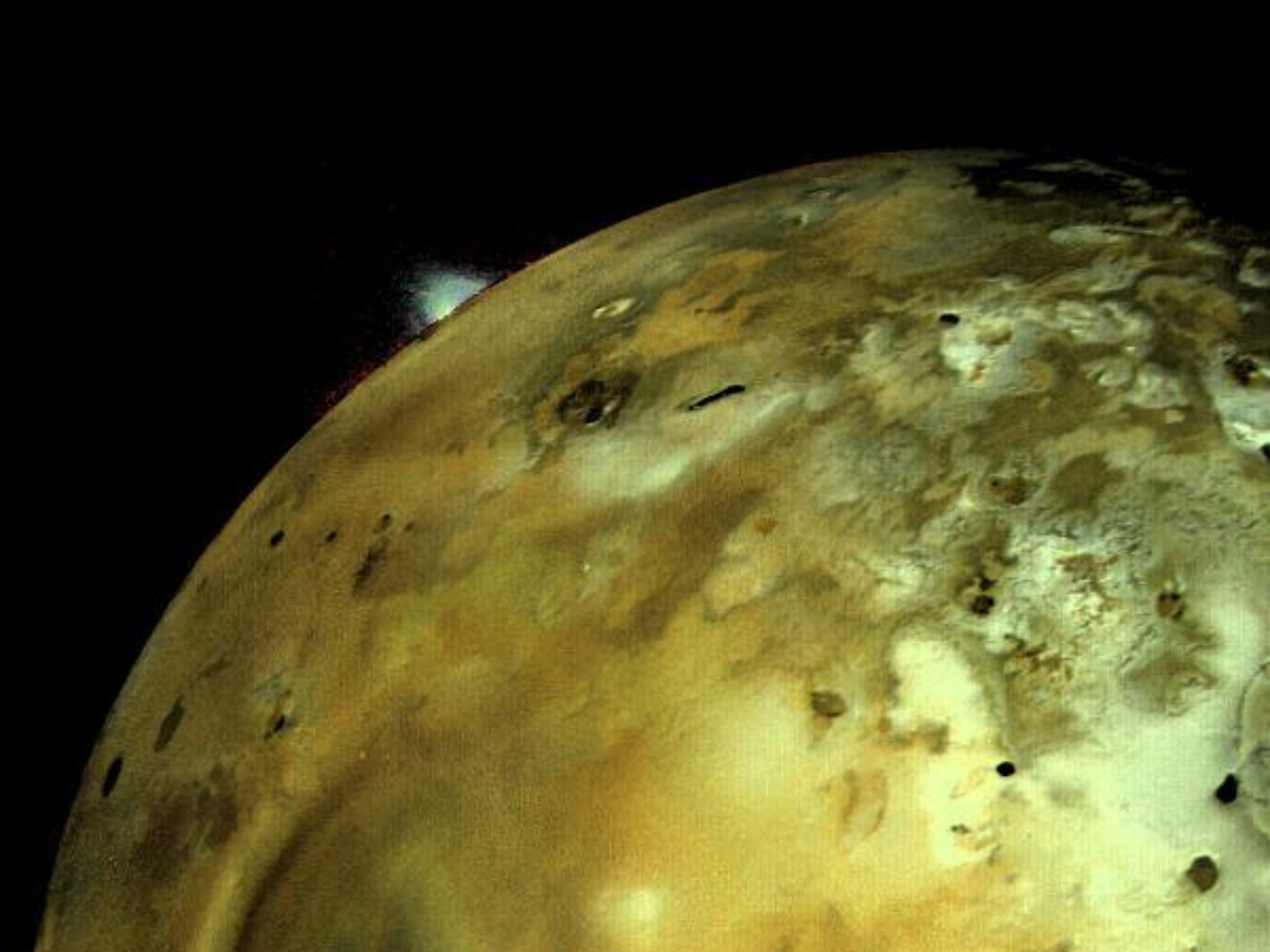
NASA


119
129
49
59
79
69
77

Voyager 1+2



Earth 20 Aug 77
Jupiter
9 Jul 79
Saturn
25 Aug 81
Uranus
24 Jan 86
Neptune
25 Aug 89
Voyager 2 velocity
Solar system escape velocity
Heliocentric velocity (km/s)
Distance from sun (astronomical units)
0
5
10
15
20
25
30
35
40



THE GENERATION OF NONAXISYMMETRIC MAGNETIC FIELDS IN THE GIANT PLANETS

D. MOSS

Mathematics Department, The University, Manchester M13 9PL, UK

A. BRANDENBURG*

Advanced Study Program and High Altitude Observatory,
National Center for Atmospheric Research†*,*
P.O. Box 3000, Boulder, CO 80307-3000, USA

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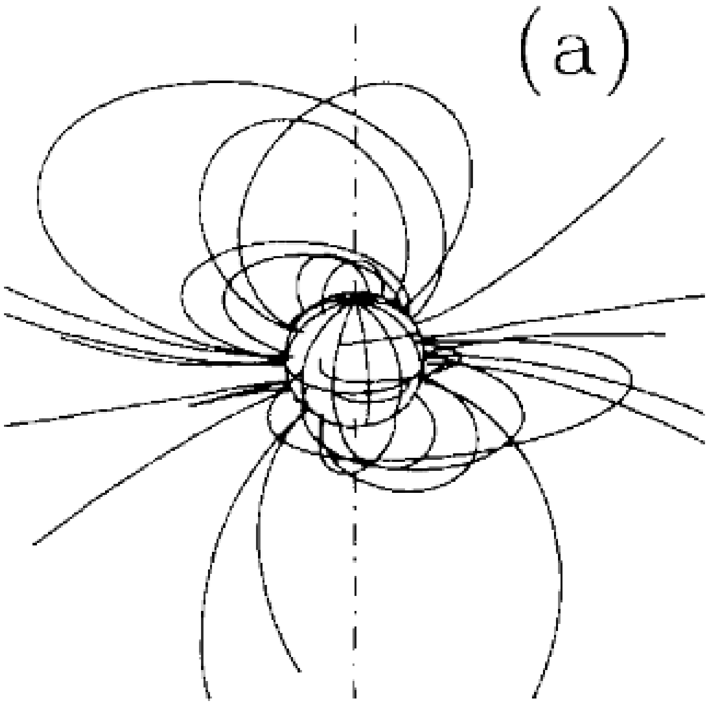
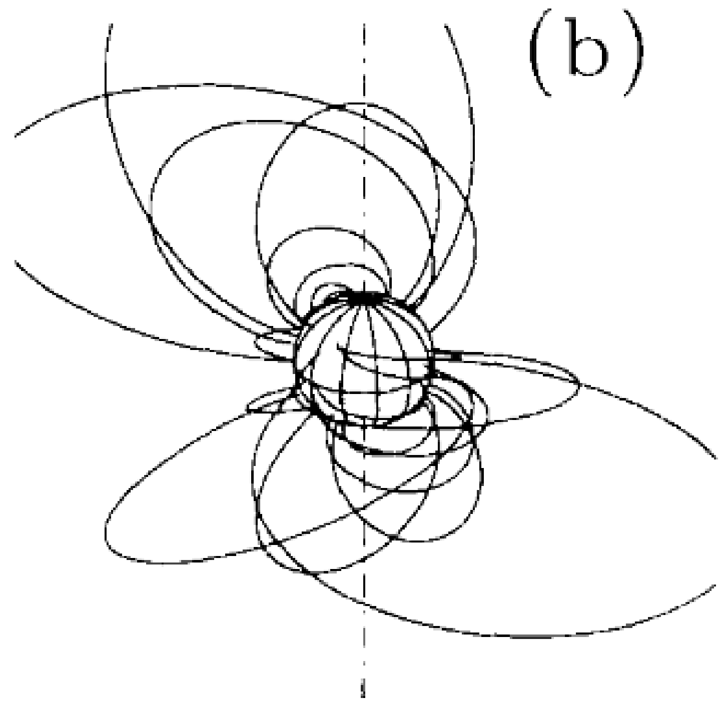
1. INTRODUCTION

The dipole moments of the magnetic fields of Jupiter and Saturn are quite closely aligned with the rotation axes, in contrast to the magnetic fields of Uranus and Neptune which are highly nonaxisymmetric with dipole moments almost perpendicular to the rotation axes. The origin of this difference is very puzzling. Possible explanations include that Uranus and Neptune just happen to be in a state of field reversal, similar to the reversals found in geological records of the earth's magnetic field (Schultz and Paulikas, 1990; Rädler and Ness, 1990), or that the types of dynamos that operate in Uranus and Neptune are fundamentally different from those of Jupiter and Saturn (Connerney *et al.*, 1991), in that the fields of Uranus and Neptune are generated close to the surfaces of these planets, whereas the fields of Jupiter and Saturn are generated in deeper layers. For example, Stevenson (1982) proposed that the very high



Uranus & Neptune
(less differential rotation)



Jupiter & Saturn
(more differential rotation)

We thank Günther Rüdiger for pointing out the need for these investigations, and Fran Bagenal, Paul Charbonneau, John Hart, and Michel Rieutord for discussions and further references concerning the physics of the outer planets.

References

Bagenal, F., "Giant planet magnetospheres," *Annu. Rev. Earth Planet. Sci.* **20,** 289–328 (1992).

What we learned today

- Solar wind turbulence
  - Energy spectrum
  - Dimensional analysis
- Heliosphere & termination shock
- Voyager 1 + 2
  - Messages to us & from us
  - Magnetic fields of planets